FINNISH EXPERIENCE WITH A PAVEMENT MANAGEMENT OPTIMIZATION SYSTEM

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The Finnish National Roads Administration (FinnRA), with support from the consulting firms Viasys Oy of Finland and Cambridge Systematics, Inc. of the USA, has developed a national economic model to optimize pavement rehabilitation policy and the allocation of funding. The model has been operational for all of the country's asphalt-surfaced roads for three years (1), and for all of its light pavements for one year. It is able to analyze general rehabilitation procedures ranging from general patching to total reconstruction for all of the nation's 45,000 km of pavements, evaluate the need for converting oil gravel pavements to asphalt concrete, and analyze the distribution of funding between the two types of pavements. Since it is a network-level model, the system analyzes policies at an aggregate level, considering only classes of roads, or sub-networks. A separate Project Analysis System (2), now used in the district offices, relates the policy and budget recommendations of the network optimization to specific databases of road segments.

Central to the optimization model is a Markov dynamic program, which has been formulated as a linear programming problem for solution by off-the-shelf software. The dynamic program categorizes pavements into 135 condition states and eight actions (108 states and five actions for light pavements), and represents deterioration as the probability of making transitions among all possible pairs of states over one year. An agency cost model estimates the cost of each possible action, and a user cost model evaluates the results in terms of travel time, fuel consumption, and vehicle depreciation. In selecting optimal actions for each possible condition state, the model tries to find a level of rehabilitation which balances the higher user costs of poor maintenance against the higher agency costs of good maintenance.

Separate models are available for each permutation of two climatic regions and three traffic volume classes; the Markov model optimizes budget allocations within each of these six sub-networks, and an incremental benefit-cost procedure based on parametric analysis results, optimizes the allocation of funding among them and between light pavements and asphalt concrete.

1. OVERALL MODEL STRUCTURE

The Finnish National Road Administration and the thirteen district offices are highly independent in their day-to-day activities, with the central Administration playing an administrative role and providing consulting services in new technologies and road and traffic research. Each year the Administration prepares rehabilitation and maintenance budgets and negotiates objectives with the districts and the Ministry of Transportation.

Annual and long-term road management objectives are set for each district, and these are strictly tied to the coming budget. The districts execute all maintenance actions, with the central office taking little interest in the specific actions chosen as long as overall objectives are met. Objectives are set for one-year and five-year periods by mutual negotiation with the Director General of the Administration and the Districts' Chief Engineers; this is then approved by the Ministry of Transportation. The results are monitored over the following year.

Using the HIPS models, the optimal objectives, road policy, and strategy are defined for the long-term and short-term, in order to bring the road network to desired condition levels. The districts then prepare the capital program, including the definition of projects, actions, locations, and costs. Accomplishment of the objectives is judged by annual measurements taken in the fall.

The actual implementation of maintenance measures is done either by the districts' own forces or by contractors. The central Administration sets maintenance and design standards for this work and provides funding consistent with these standards.

To address this division of responsibilities, the pavement management system consists of two separate software packages:

- **Network level**, embodied in the HIPS, which addresses abstract categories of roads and the allocation of funding among them. The HIPS helps the central administration to determine the funding level for each district, and develops policy guidelines on how the money is to be used.
- **Project level**, embodied in the Project Analysis System (PAS), which guides the district engineer in matching the network-level policies with detailed databases of roads which already exist in each district.

Although both the districts and the central administration are potential users of the entire system, the central office is the primary user of the relatively abstract modelling and allocation procedures in the HIPS, while the districts are the primary users of the more detailed PAS. Several levels of analysis are provided in the HIPS to address the capital programming policy questions of interest to the highway Administration. These are the:

- **Pavement type** level, which distinguishes asphalt concrete pavements from light pavements.
- **Region** level, which distinguishes the cold and relatively dry interior and northern parts of the country from the more temperate and moist southern coastal area. Climatic differences affect the behavior of pavement deterioration and the choice of maintenance policy.
- **Volume class** level, which affects the rate of deterioration of pavements as well as the level of user costs associated with pavement condition. Much of the modelling work occurs on the level of the twelve permutations of pavement, region and volume class, termed the **P/R/VC** level.

- **National**-level, which accumulates the results from the pavement types, regions and volume classes to address national funding levels and funding allocations.
- **District**-level, reflecting the thirteen maintenance districts which are the recipients of capital funding and which carry out all of the programmed work. Each district is contained within one region, and has roads representing all three volume classes.

As in any far-sighted capital programming process, the Roads Administration is concerned with the long-range goals which should be established for the highway network, and also with the steps needed to proceed from the current situation toward the long-range goals. Since the projects addressed by the pavement management system are largely ones of in-kind facility replacement and major maintenance, the Administration would like decision-making in this area to concentrate on direct economic benefits and costs to road users. This leads to the next important division within the HIPS:

- **Long-term** model, which analyzes possible long-term goals and tries to find a future policy which minimizes social costs (the sum of user and agency costs) and is sustainable indefinitely into the future. The long-term model is not tied to the current condition of the network and imposes no requirements on which specific year it should be achieved.
- **Short-term** model, whose first priority is to find the quickest practical means of achieving the level of network condition which would make the long-term policy possible; and whose second priority is to minimize the social costs incurred in the short-term period between now and the time when the long-term goals are achieved.

As shown in Figures 1 and 2, the flow of activities in using the HIPS starts at the most abstract level and ends at the most concrete. The long-term model analyzes the general behavior and cost structure of roads in each of the six subnetworks of region and volume class, and then uses an incremental benefit-cost model to determine the best allocation of funding among them. It defines goals broadly and at some undetermined time in the future. This then proceeds to the short-term model (Figure 2), which is more concrete because it is explicitly tied to the current observed condition of the road network, from the Road Data Bank. Following this, the analysis becomes even more concrete in the short-term budget allocation step, an activity of immediate interest to the managers within the administration and the districts. Finally, the least abstract activity is the definition of actual projects on specific roads, in the Project Analysis System. This flow of abstraction follows the general flow of the Administration's planning process, and provides a way in which the economic merits and costs of rehabilitation policy can be conveniently merged with the non-economic and political considerations which also determine the ultimate budget allocations and capital program.

In both the long-term and short-term analyses, the central feature is an economic model of pavement behavior, rehabilitation policy, and their combined social cost implications. The main components of the economic model are:

Figure 1. Long-Term Goal-Setting

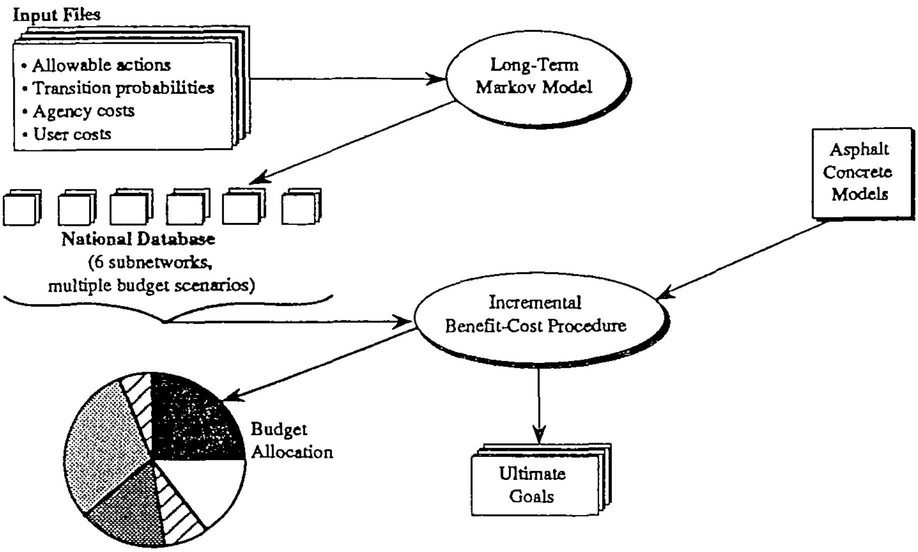
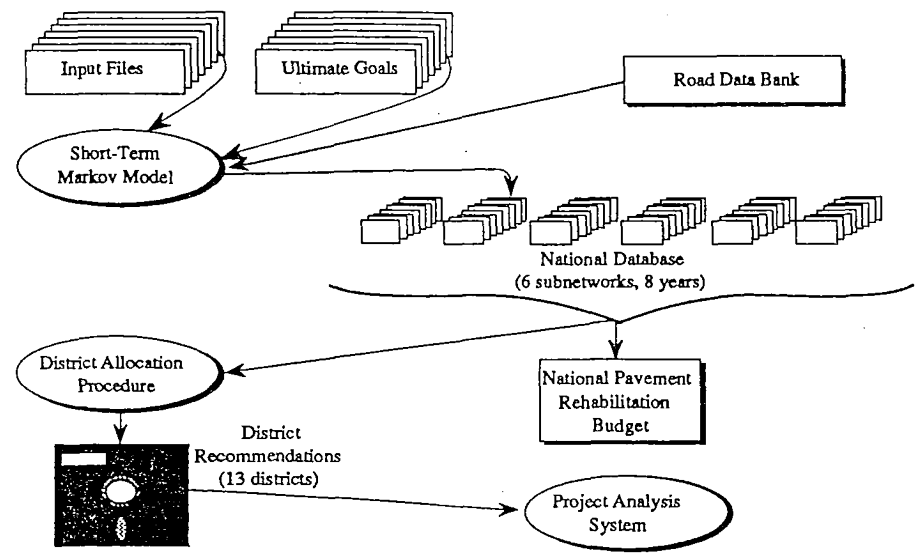


Figure 2. Short-Term Budgeting



- **Agency cost** model, giving the average construction costs for eight general categories of rehabilitation action, from Do-Nothing to Total Reconstruction.
- **User cost** model, which quantifies in economic terms the increase in travel time, fuel consumption, vehicle wear-and-tear, and accidents associated with deteriorated road condition.
- **Deterioration** model, describing the process by which a road deteriorates and thereby causes higher user costs to be incurred. Similarly, it also describes the improvements which can be expected after each of the general rehabilitation actions is applied.

It is to be expected that, as the expenditure of agency costs increases, the resulting level of user costs will decline, as long as the available money is always used in the most cost-effective manner; also, as agency costs decrease, user costs go up. The economic optimization framework assumes that there is an intermediate point where social costs, the sum of user and agency costs, is minimized. Policy questions which are addressed in the framework are:

- What is the optimal (social-cost minimizing) level of expenditure on pavement rehabilitation and major maintenance on the nationwide road network, and within selected sub-networks?
- At funding levels which do not minimize social costs, what is the optimal allocation of funding among sub-networks, and what is the most cost-effective means of spending the available money: what is the best overall allocation among action types, and what specific actions should be applied to what kinds of roads?
- To what extent do budget constraints increase the level of costs borne by road users, and what does this tell us about the importance to society of user costs relative to agency costs?
- How much better is the long-term optimal solution than the current situation, and how long must it take to achieve the long-term goals?

Many different modelling methodologies can be applied to these questions. At the beginning of the earlier development effort for asphalt concrete, a thorough review was conducted of the experiences of US and international organizations using many different techniques. The methodology finally selected was an adaptation of Markov dynamic programming, a technique which had been used in optimization applications as diverse as fleet replacement, catalog mailing list selection, timing of bond calls, and purchase of satellites (3). At the time, the only full-scale implementation of the technique in pavement management was in Arizona (4). Since then, Markov models have been applied to Bridge Management Systems also (5).

Markovian models are very attractive for this application because they are intuitive to managers; they recognize stochastic behavior and the dynamic nature of pavement decisions explicitly; and computational processing is fast and efficient on micro-computers.

Both the HIPS and the PAS are menu-oriented and very user-friendly. All through the system, analytical and summary reports and screen displays are available to show how the models are developing. A convenient filing system manages the input and output files on the hard disk and allows the user to keep track of multiple versions of an analysis archived on floppy disks or hard disk subdirectories. All activities involved in using the HIPS are available from a menu hierarchy; at each "leaf" of the menu "tree," a screen representing the module or report explains the purpose of the module and allows the user to fill in various options which are available for that module.

2. INPUT DATA AND ORGANIZATION OF THE MARKOV MODELS

The formulation and organization of the Markov models is loosely based on the formulation used in Arizona, but conditions are categorized in a much different way, and user costs are included explicitly in the objective function. Also, the desire to implement the system on micro-computers has introduced both design constraints and design opportunities which, in the end, have led to a system which is quite unique. Markov dynamic programming can be distinguished from other optimization approaches by several features:

- Problems are structured into multiple **stages**, which are solved one stage at a time. All the stages are structured identically to each other, and all have the same possible outcomes. The stages are evenly separated from each other in a uniform progression, usually in time.
- The range of possible outcomes of each stage is expressed as a set of discrete **states**. It must be possible to write out a reasonably short list containing every possible result.
- The outcome of any particular stage depends stochastically on the outcome of the stage before it, and not on the outcomes of any of the other stages. Because of this, Markov dynamic programs are said to have "one-step memories."

By applying a Markov model recursively over a series of stages, it is possible to predict probabilistically the outcome of any future stage. Such a series of Markov predictions is called a **Markov chain**.

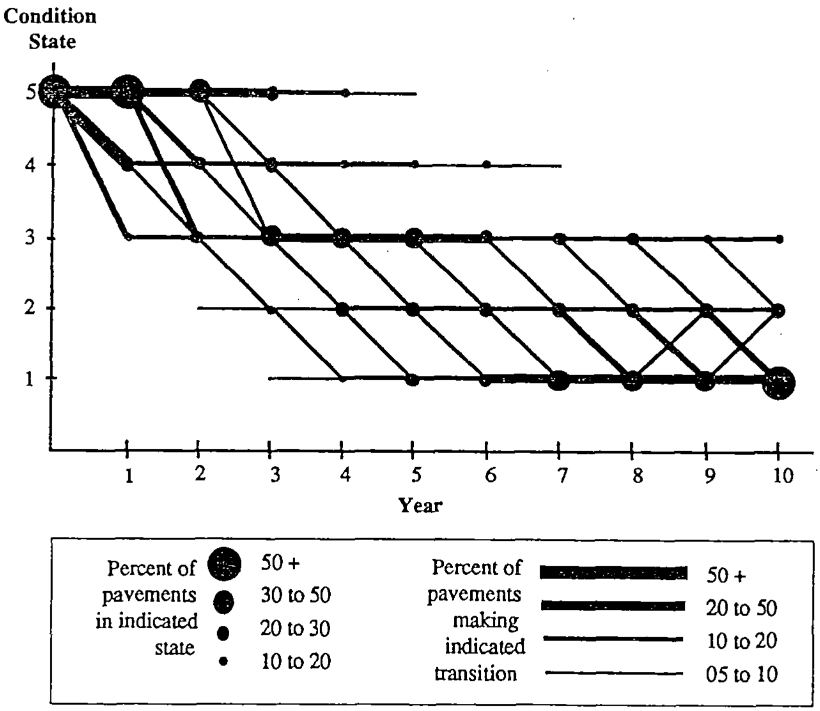
For the purposes of Finland's pavement management system, each stage is a description of the condition of the road network in a given year in terms of the distribution of roads among the set of possible states, combined with the choice of action taken in that one year. Figure 3 shows how, in a system of 5 states, a Markov chain of deterioration plays out for a road starting in the highest state. As expected, the road ends up in the lowest possible state eventually, but the path it uses to get there may vary. Although such a stochastic prediction may be of limited use in designing the treatment for any particular road, it is very useful for characterizing a whole road network. The matrix of probabilities of transitions from each state to each other state in one year, for each action, is the fundamental deterioration and performance model used in the HIPS.

The number of volume classes is considered to be sufficient to give the desired policy sensitivity at the network level. However, the most interesting geographic division is among districts, of which there are thirteen. It was decided that having the resulting 39 separate models would be too difficult and time-consuming, though, and so the higher level of aggregation to just two regions was used. Later in the sequence of events depicted in Figure 2, a District Allocation Procedure takes the region-level results and allocates them back to the district level as needed.

The following condition measurements are used to characterize the condition state of a pavement (number of classes in parentheses):

Asphalt Concrete	**Light Pavements**
Bearing Capacity (5)	Bearing Capacity (4)
Defects (Cracking/Patching, 3)	Distress Index (3)
Rut Depth (3)	Longitudinal Roughness (3)
Roughness (3)	Transverse Roughness (3)
Total States: 135	**Total States: 108**

Figure 3. Markovian Deterioration



Bearing capacity is considered to be the major factor inherent in a pavement which affects its subsequent deterioration, but distress and roughness also have this effect to a lesser degree. Distress and roughness both have an effect on user costs.

Data are continually being developed by the Administration to update and improve the deterioration and cost models. For the do-nothing action category (which includes routine maintenance), transition probabilities are directly estimated from the Road Data Bank; for other actions, probabilities are developed from a Delphi process of interviewing expert engineers. Agency cost factors are developed from the Administration's own historical records, while user costs are estimated by the Administration's Research Center from experimental evidence and economic data.

3. MARKOV MODEL FORMULATIONS

Mathematically, the long-term Markov model assumes a steady-state distribution of pavements among the condition states. This does not mean that each road is always in the same condition, but it does mean that, in every year, the same overall fraction of roads may be found in the same state. It also means that the same fraction of roads undergoes the same general action each year. This is all part of the requirement that the long-term program be not only optimal, but also sustainable, indefinitely.

Of course, the condition distribution among the condition states measured today is generally not equal to the long-term optimal distribution. In fact, the long-term model is not in any way tied to the current condition distribution or current rehabilitation policy, but represents instead a goal that might be attained at some time in the future. What makes the goal desirable is that it minimizes social costs. For the purposes of translating the model to a linear program, the social cost of the long-term program is calculated in the following manner as the objective function to be minimized:

$$\text{Social cost} = \sum_{a} \sum_{i} W_{ai} \left(C_{ai} + \varnothing \, U_{ai} \right)$$

where:

W_{ai} is the decision variable, the fraction of all pavements which are in state i and have action a applied to them.

U_{ai} is the user cost factor in marks per km

C_{ai} is the agency cost factor in marks per km

$\varnothing$ is the degree of user cost contribution to the objective function, usually 1. It can be varied in an automated parametric analysis provided in the HIPS

To prevent "leakage" from the system, and to give scale to the W_{ai} decision variables, the first constraint on the linear program is a definitional unity constraint:

$$\sum_{a} \sum_{i} W_{ai} = 1$$

The most important element of the formulation is a constraint which combines the Markov model with the requirement of a steady state:

$$\sum_{a} \sum_{i} W_{ai} \; P_{aij} \; = \sum_{a} W_{aj} \text{ for all j}$$

where:

P_{aij} is the transition probability of going to state j in year t+1, given state i in year t, when action a is applied in year t, which does not depend on t

This constraint starts with the distribution of condition states and actions in one year, represented by i, applies the transition probabilities to get the distribution in the next year, represented by j, and then says that this resulting distribution must be the same as in the previous year, so that all years have the same condition distribution. Loosely interpreted, this means that, for every km of road leaving any given state, another km must arrive in that state to replace it. Next comes an optional budget constraint, which can force the agency cost total to a level either higher or lower than the social-cost minimization level:

$$BMIN \leq \sum_{a} \sum_{i} W_{ai} \; C_{ai} \leq BMAX$$

where:

BMAX and BMIN are budget constraints, in marks per km, which can be varied in an automated parametric analysis

Finally, the long-term model has optional condition constraints. To make these most relevant and usable, condition constraints are applied to condition classes, rather than states. Each state belongs to four different classes, one in each condition variable. The constraints are:

$$CMIN_c \leq \sum_{i \subset c} \sum_{a} W_{ai} \leq CMAX_c \text{ for all c}$$

where:

$CMAX_c$ and $CMIN_c$ are fractions which represent the limits on the total fraction of pavements allowed to be in each class.

The parametric analyses on user cost contribution and budget constraints are very important. Both capabilities produce a series of different scenarios where different levels of agency costs are incurred and different levels of user costs result. These are used in the allocation of resources among the sub-networks, using the incremental benefit-cost procedure (1). They are also used in a specialized report which compares the long-term performance of asphalt and oil-gravel pavements to determine at what traffic volume the latter should be upgraded.

The short-term Markov model is similar, but its objective is to maximize the amount of progress made each year toward the long-term optimal objective, given budget constraints.

4. PRACTICAL RESULTS OF HIPS

HIPS produces many different reports relevant to management decision-making for pavement rehabilitation. The following table is one interesting example, which compares current conditions with long-term optimal conditions for high-volume (>6000 ADT) asphalt pavements in southern Finland (percent of road km).

Condition Variable	Class-Limits	Current Condition	Optimal Condition
Roughness	IRI < 1.5 mm/m	8.1	76.0
	1.5 <= IRI <= 3.5	88.1	23.7
	IRI > 3.5 mm/m	3.8	0.3
Bearing Capacity	> 330 MN/sq.m.	81.6	90.3
	311-330 MN/sq.m.	3.1	3.4
	251-330 MN/sq.m.	6.5	2.8
	211-250 MN/sq.m.	3.9	2.1
	<=210 MN/sq.m.	4.8	1.4
Defects	< 1% of length	62.4	96.1
	1-20% of length	35.9	3.3
	> 20% of length	1.7	0.6
Rutting	0-13 mm	65.4	57.3
	13-19 mm	31.8	24.4
	> 19 mm	2.8	18.3

The results show that the current condition distribution is not optimal. More effort should be placed on improving bearing capacity and roughness.

Another useful example is the analysis of funding requirements. The current funding for maintenance and reconstruction of all AC roads is about 40000 FIM's per kilometer per year. HIPS results (below) show that the investment on road maintenance should depend more on traffic volume.

Region	Traffic (ADT)	Funding kFIM/km/year
South	> 6000	60
	1500-6000	66
	< 1500	31
North	> 6000	84
	1500-6000	37
	< 1500	23

One eagerly-awaited result is the traffic volume level at which an asphalt-concrete road has a more attractive long-term cost profile than oil-gravel. This is one possible warrant for pavement upgrading. The HIPS results placed this threshold traffic volume at 817 in southern Finland and 862 in northern Finland.

With policy-relevant results such as this, HIPS has been very useful to FinnRA management for illustrating deficiencies in the road network, estimating funding needs, and performing "what-if" analysis of budget and policy scenarios.

5. CURRENT USAGE AND FUTURE PLANS

HIPS is now used routinely by the central administration for the kinds of policy questions illustrated above, and as one input in the process of allocating money among districts. FinnRA has provided the software to all thirteen of its districts and given a two-day training course, but so far no district has adopted it. This is not totally surprising, given the system's network-level perspective and the relatively sophisticated analytical methods used. Still, FinnRA would like to continue to encourage the districts to use the system, to make their budget requests more consistent with administration policy.

The most important problems encountered in HIPS implementation are typical of PMS implementation experiences with other systems in other countries:

- Input data which are insufficient and inaccurate, a problem which only this year appears close to an adequate solution, with new data-collection methods FinnRA has implemented.
- Wavering commitment to the PMS by top management, which has experienced personnel changes since HIPS was developed. It appears that the administration's staff analysts are the driving force in keeping the system operational.
- The agency has not dedicated the resources necessary to translate the software and manuals to Finnish, so most of the users are those who speak English.
- The analytical methods of any budget analysis tool are unfamiliar to staff who have only civil engineering training. This is another kind of language barrier that is difficult to overcome.

FinnRA staff believe that these problems can be overcome, with sufficient training and promotion of the system. The approach taken in HIPS is particularly helpful in minimizing data requirements, compared to other PMS approaches, but its analytical sophistication makes the selling of the system to engineering management more difficult. The quality of HIPS input data and output information improve each year, as does management familiarity with the system. There is therefore every reason to believe that the system will remain useful and will expand its constituency over time.

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